ECCO2: Global Ocean and Sea Ice State Estimation in the Presence of Eddies

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Need for high resolution, for sea ice, and for a physically consistent solution.

A first ECCO2 solution was obtained using a Green's function approach to adjust a small number (~80) of model parameters.

Early science applications include impact of mesoscale eddies on large-scale ocean circulation, studies of polar oceans, and ocean biogeochemistry,

A follow-on ECCO2 solution is being obtained using the adjoint method to adjust ~10^9 model parameters.

http://ecco2.org/

Need for high resolution

Eddy-parameterizations are not based upon fundamental principles and fail to adequately account for flow anisotropies leading to flux errors that accumulate and change large scale ocean circulation in important ways.

Narrow western and eastern boundary currents make major contributions to scalar property transports but are not parameterizable. Until they are resolved, there will be doubts that ocean models carry property transports realistically.

Inability to resolve major topographic features (e.g., fracture zones, sills, overflows) leads to systematic errors in movement of deep water masses with consequences for accuracy of water mass formation and properties.


Hill et al., 2007
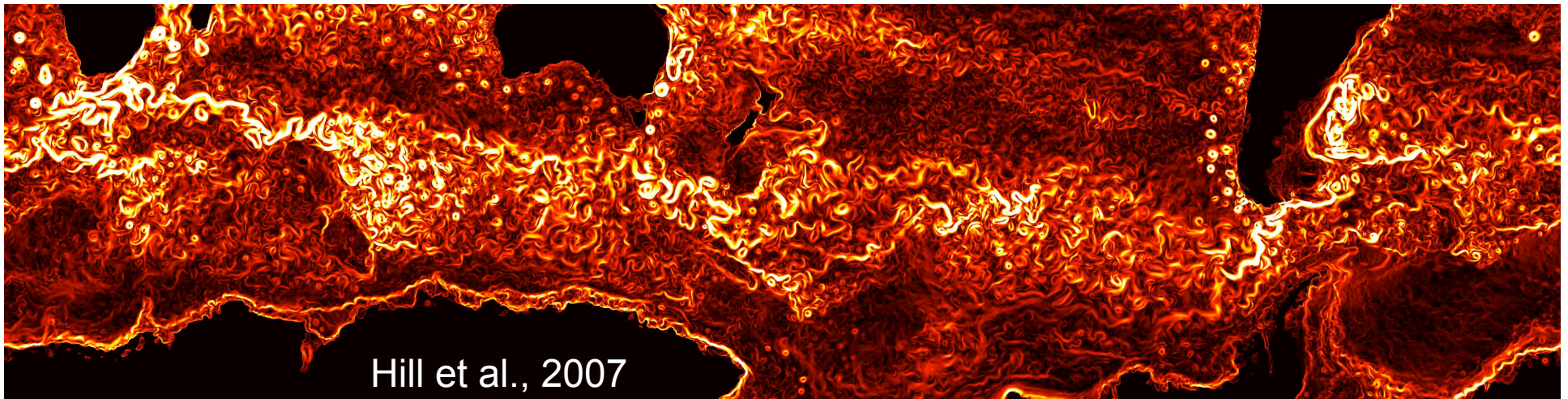
Need for sea ice

Sea ice affects radiation balance, surface heat and mass fluxes, ocean convection, freshwater fluxes, human operations, etc.

Sea-ice processes impact high-latitude oceanic uptake and storage of anthropogenic CO_2 and other greenhouse gases.
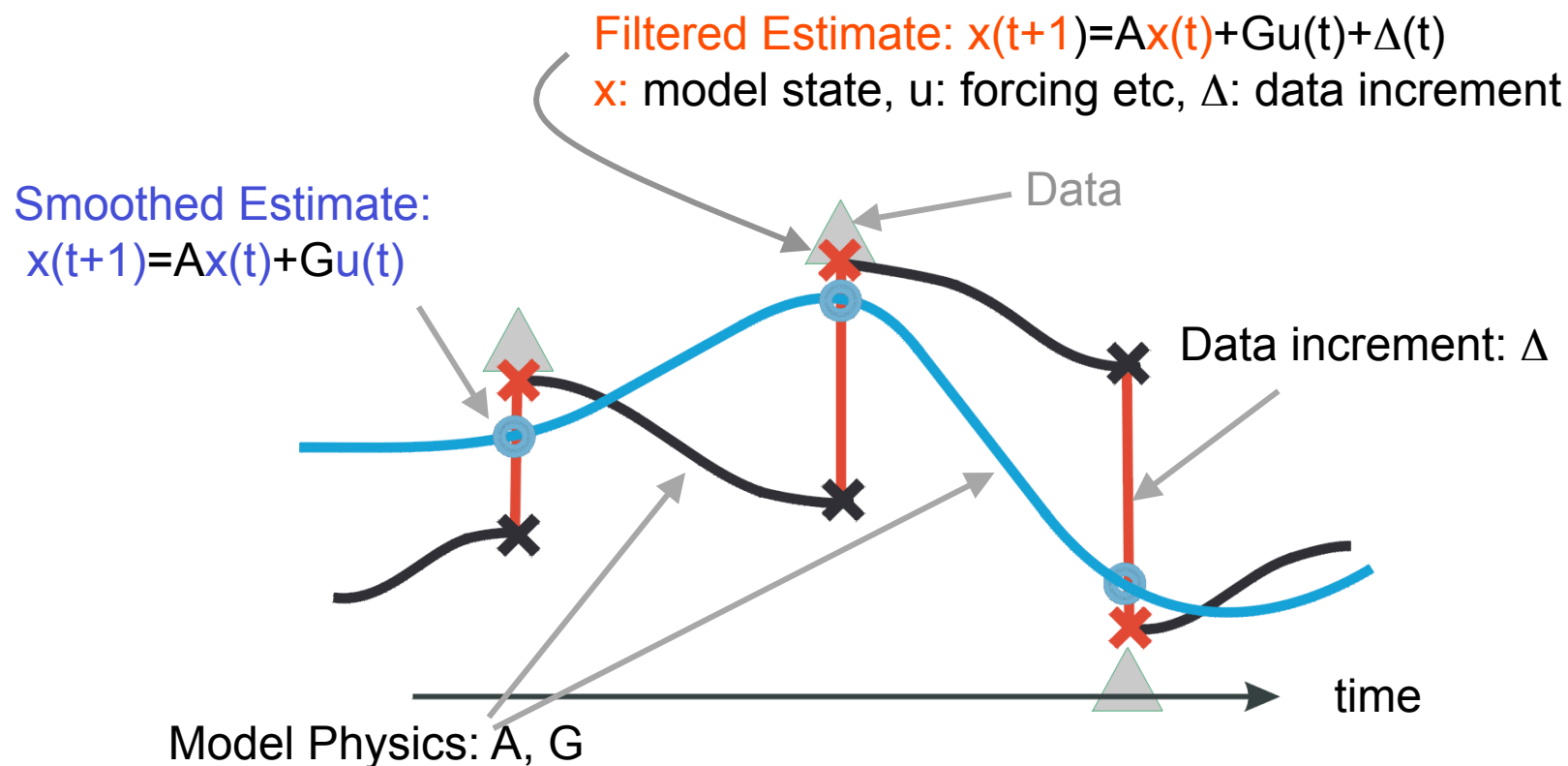
Inclusion of a dynamic/thermodynamic sea ice model permits fuller utilization of high-latitude satellite data.
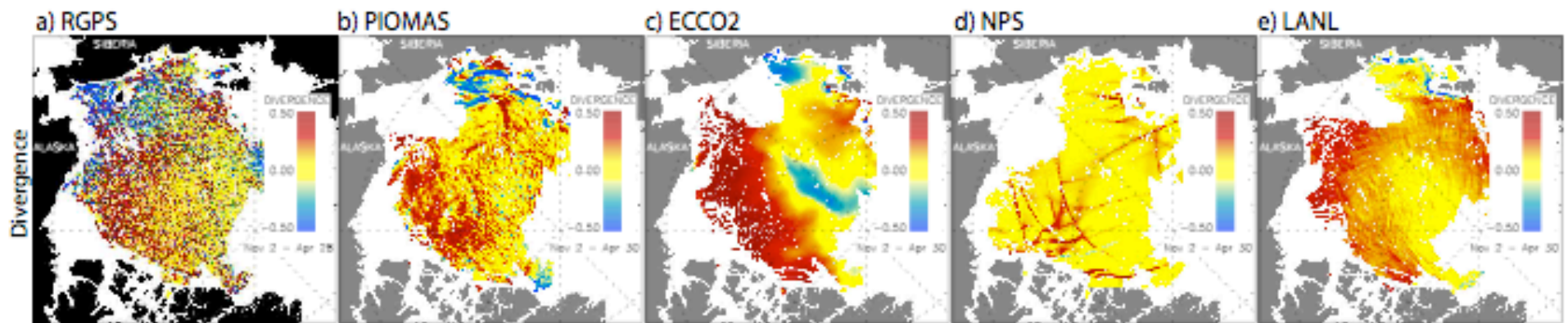
Kwok et al., 2008

# Need for physically consistent assimilation

The temporal evolution of data assimilated estimates is physically inconsistent (e.g., budgets do not close) unless the assimilation's data increments are explicitly ascribed to physical processes (i.e., inverted).

Filtered Estimate: $x(t+1) = Ax(t) + Gu(t) + \Delta(t)$
x: model state, u: forcing etc, Δ: data increment

Data

Smoothed Estimate:
$x(t+1) = Ax(t) + Gu(t)$

Data increment: Δ

time

Model Physics: A, G

I. Fukumori, JPL

Example: Atmospheric Mass Budget

Standard deviation of NCEP **surface pressure** analysis shows that, on average, **24%** of the atmosphere's mass change is physically **unaccounted for** (I. Fukumori, JPL).

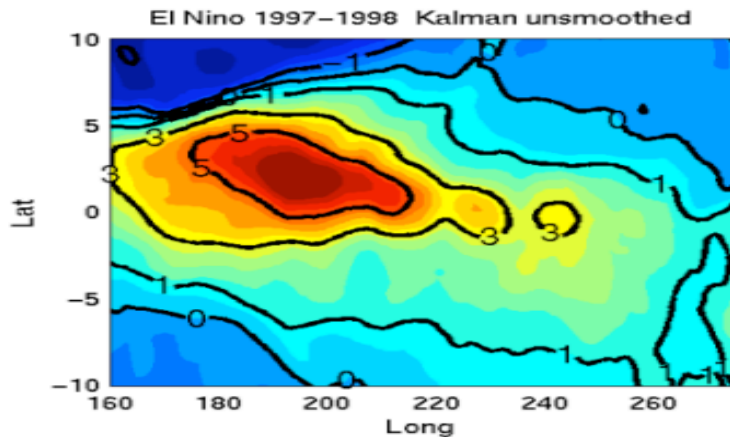Change over 6-hours
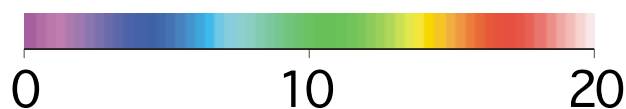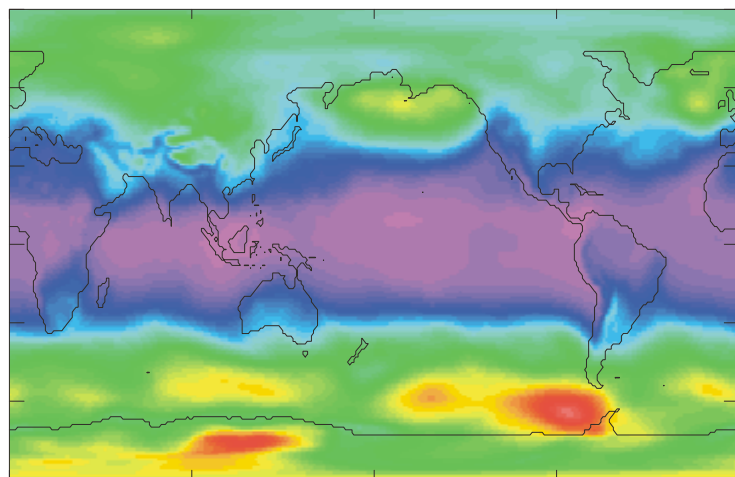
Data Increment
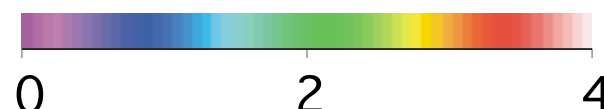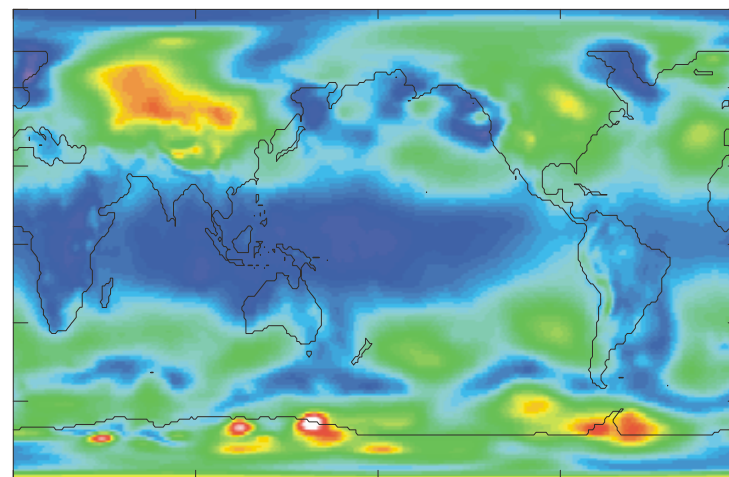
Atmospheric reanalyses contain huge air-sea flux imbalances. Compare 6.2 cm/yr freshwater flux imbalance to observed 3 mm/yr sea level rise (P. Heimbach, MIT).
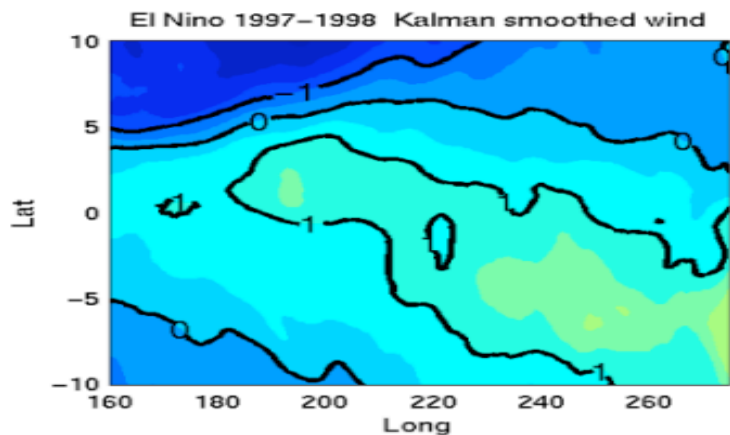
1993-2003 global mean air-sea freshwater flux	mean [cm/year]
NCEP/NCAR-I ocean $E - P$	15.1
NCEP/NCAR-I ocean $E - P - R$	6.2

Example: Sensitivity of CO_2 Sea Air Flux

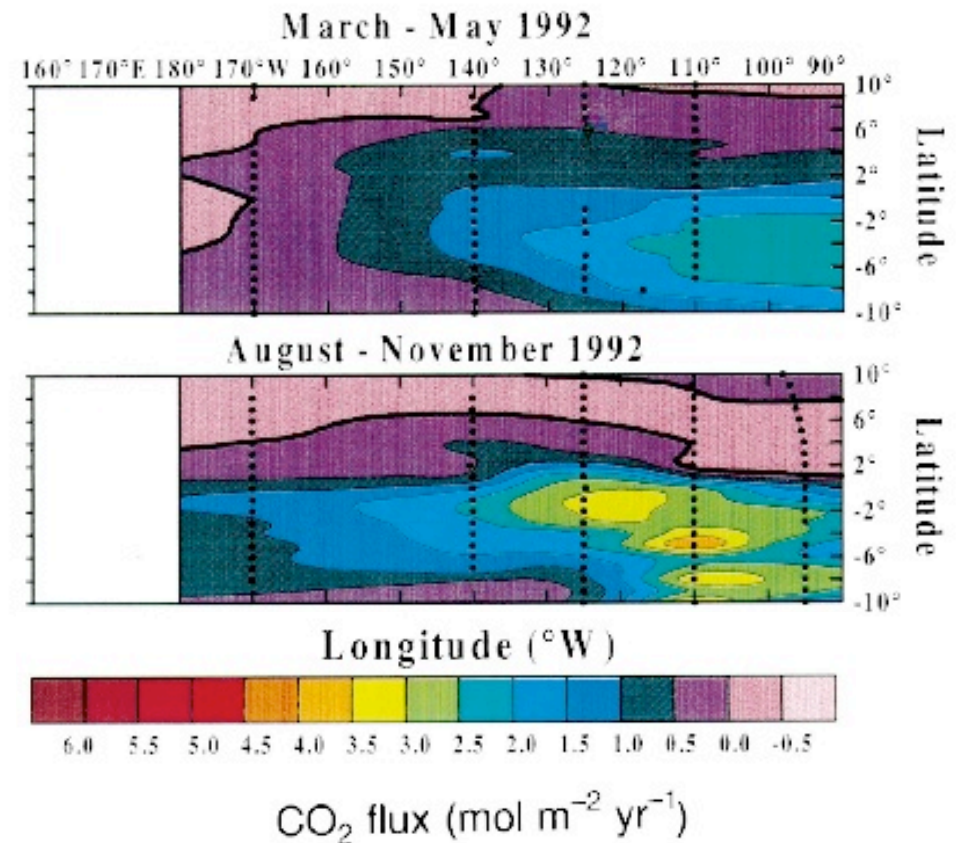Filtered estimate of CO_2 flux
during 97-98 El Niño (mol/m^2/yr)

Observed estimate of CO_2 flux
during 92-93 El Niño

Smoothed estimate of CO_2 flux

McKinley, 2002

Feely et al., 1999

1992-present Green's function optimization of CS510 MITgcm model configuration

velocity at 15 m (m/s)

Data constraints:
- sea level anomaly
- time-mean sea level
- sea surface temperature
- temperature and salinity profiles
- sea ice concentration
- sea ice motion
- sea ice thickness
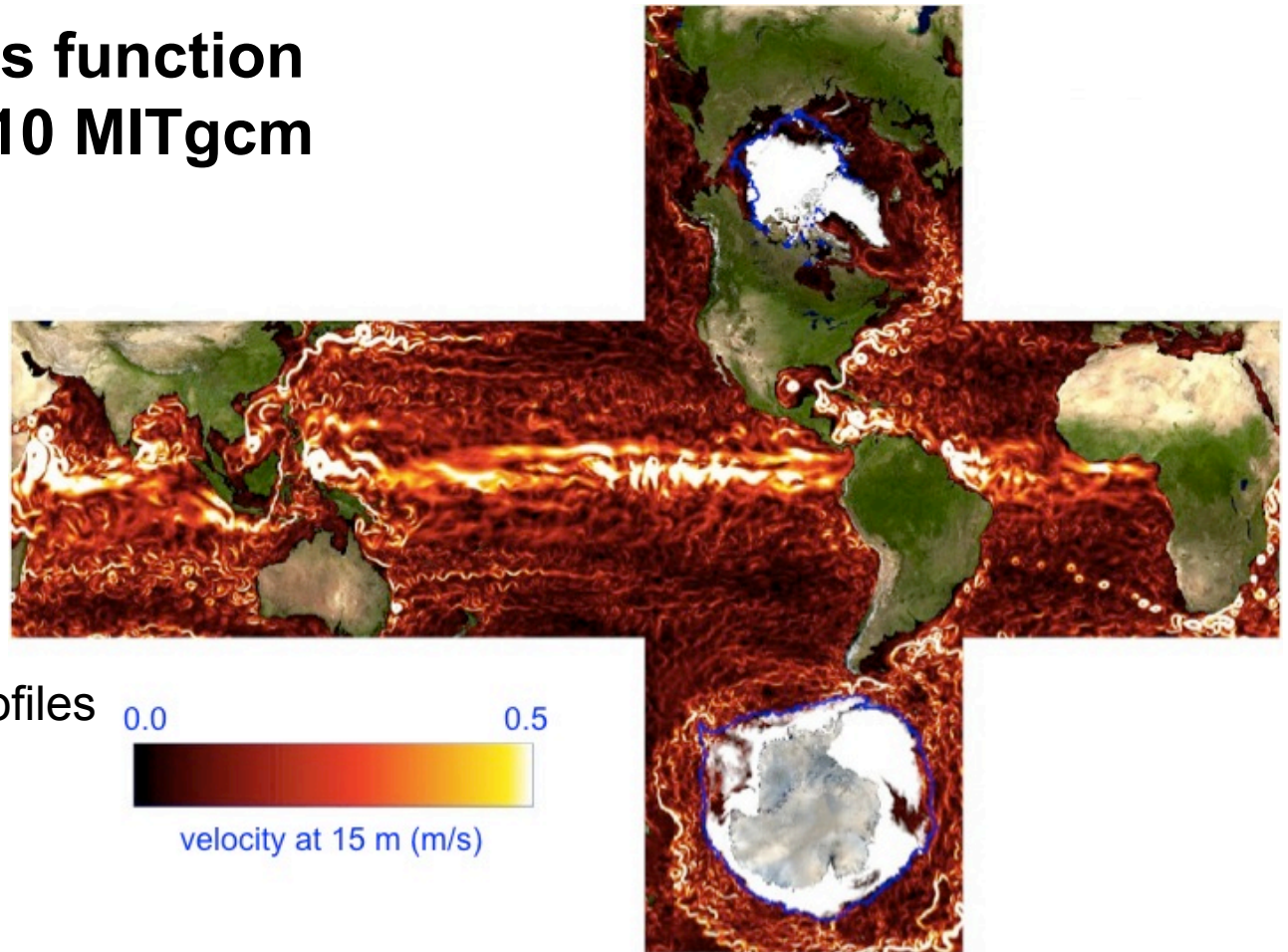
Control parameters:
- initial temperature and salinity conditions
- atmospheric surface boundary conditions
- background vertical diffusivity
- critical Richardson numbers for Large et al. (1994) KPP scheme
- air-ocean, ice-ocean, air-ice drag coefficients
- ice/ocean/snow albedo coefficients
- bottom drag and vertical viscosity

Green's Function Estimation Approach

(Stammer & Wunsch, 1996; Menemenlis & Wunsch, 1997; Menemenlis et al., 2005)

GCM: $\qquad\qquad\qquad\qquad\qquad \mathbf{x}(t_{i+1}) = M(\mathbf{x}(t_i),\boldsymbol{\eta})$

Data: $\qquad\qquad\qquad\qquad\qquad \mathbf{y}^o = H(\mathbf{x}) + \boldsymbol{\varepsilon} \qquad\qquad = G(\boldsymbol{\eta}) + \boldsymbol{\varepsilon}$

Cost function: $\qquad\qquad\qquad J = \boldsymbol{\eta}^T\mathbf{Q}^{-1}\boldsymbol{\eta} + \boldsymbol{\varepsilon}^T\mathbf{R}^{-1}\boldsymbol{\varepsilon}$

Linearization: $\qquad\qquad G(\boldsymbol{\eta}) \approx G(\mathbf{0}) + \mathbf{G}\boldsymbol{\eta}$

$\mathbf{G}$ is an $n{\times}p$ matrix, where n is the number of observations in vector $\mathbf{y}^o$ and p is the number of parameters in vector $\boldsymbol{\eta}$. Each column of matrix $\mathbf{G}$ can be determined by perturbing one element of $\boldsymbol{\eta}$, that is, by carrying out one GCM sensitivity experiment.

GCM-data residual: $\qquad \mathbf{y}^d = \mathbf{y}^o - G(\mathbf{0}) \qquad\qquad \approx \mathbf{G}\boldsymbol{\eta} + \boldsymbol{\varepsilon}$

Solution: $\qquad\qquad\qquad \boldsymbol{\eta}^a = \mathbf{P}\mathbf{G}^T\mathbf{R}^{-1}\mathbf{y}^d$

Uncertainty covariance: $\qquad \mathbf{P} = (\mathbf{Q}^{-1} + \mathbf{G}^T\mathbf{R}^{-1}\mathbf{G})^{-1}$

The solution satisfies the GCM's prognostic equations exactly and hence it can be used for budget computations, tracer problems, etc.

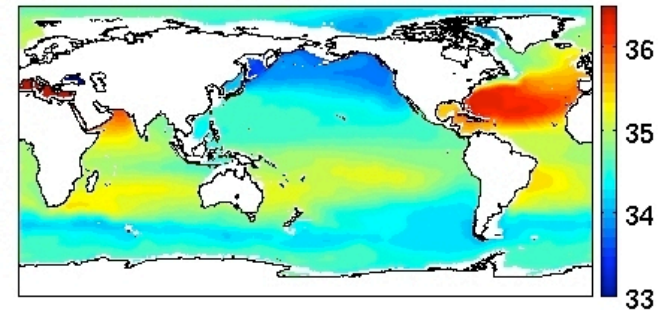# Assessment of ECCO2 vs GODAE/CLIVAR metrics (H. Zhang)

0-750-m Temperature

0-750-m Salinity

WOA05

WOA05 pot. temp. in top 750 m ($^{\circ}$C)
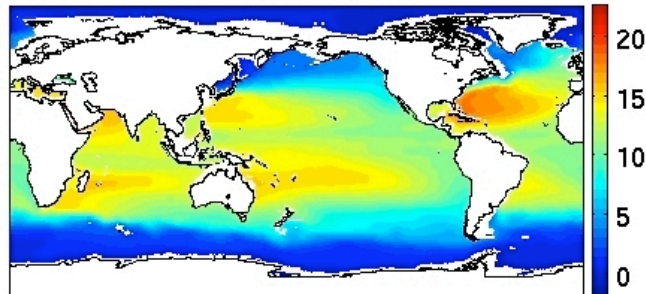
WOA05 salinity in top 750 m (PSU)

1992−2002 baseline/ WOA05 difference

ΔT of baseline wrt WOA05
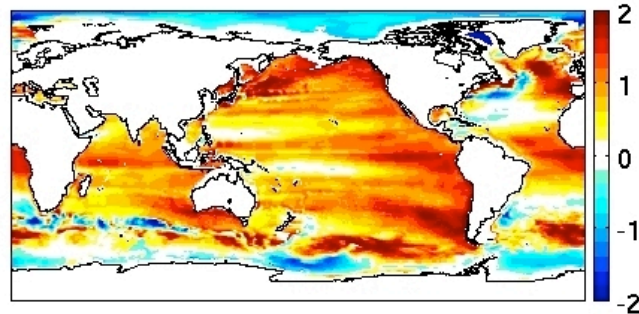
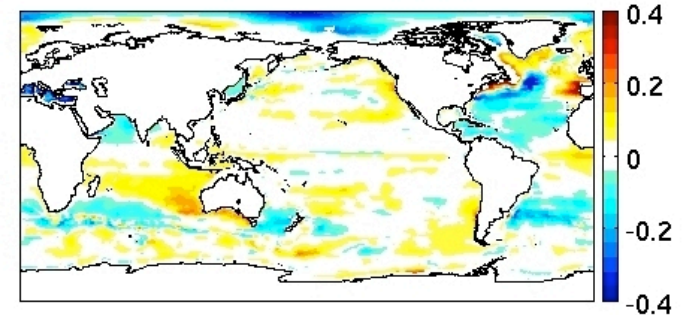ΔS of baseline wrt WOA05
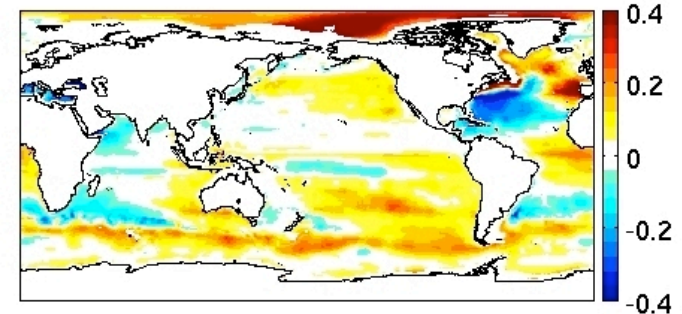
1992−2002 optimized/ WOA05 difference

ΔT of optimized wrt WOA05
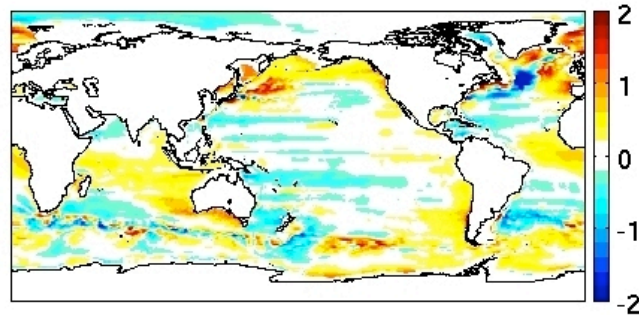
ΔS of optimized wrt WOA05
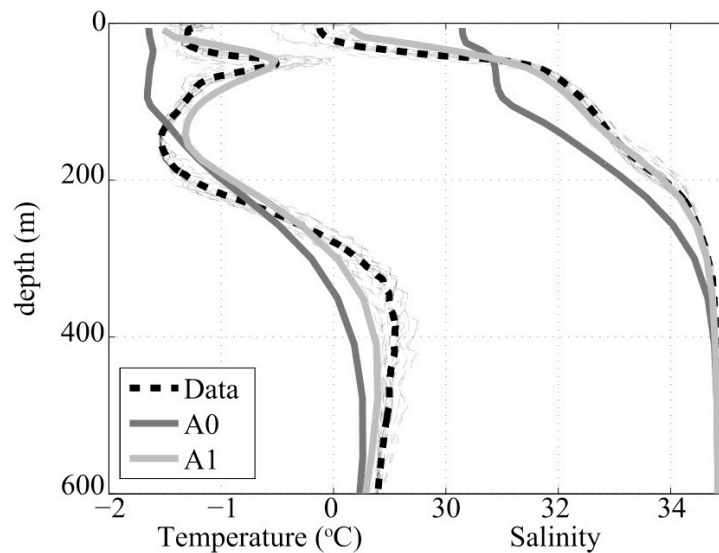
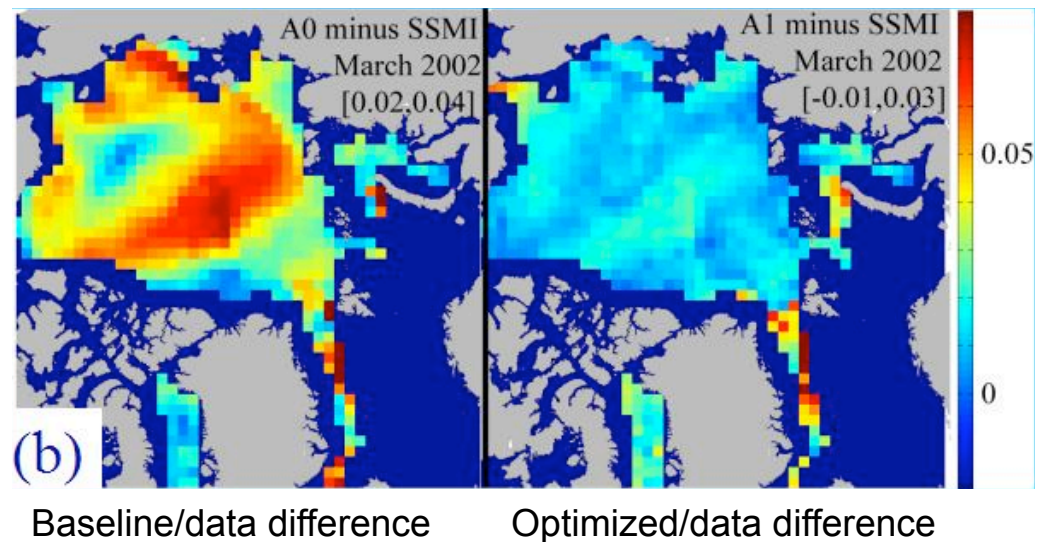# Assessment of ECCO2 in Arctic Ocean (A. Nguyen)

Arctic cost function reduction
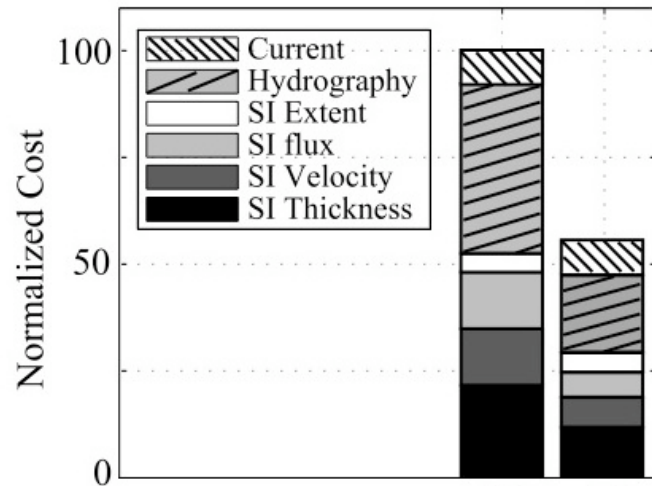
2007-2008 summer sea ice minima
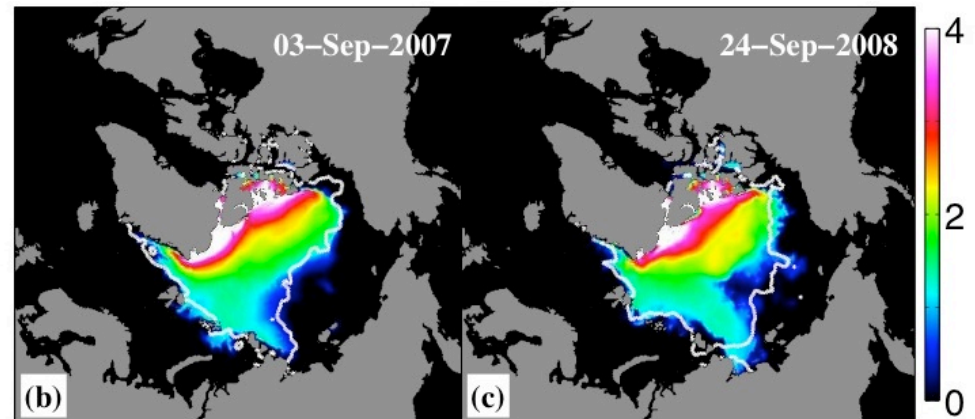
Canada Basin Hydrography

Sea ice velocity comparison with SSM/I

Baseline/data difference   Optimized/data difference

Assessment of ECCO2 in Southern Ocean (M. Schodlok)

Drake passage transport and variability

Baseline

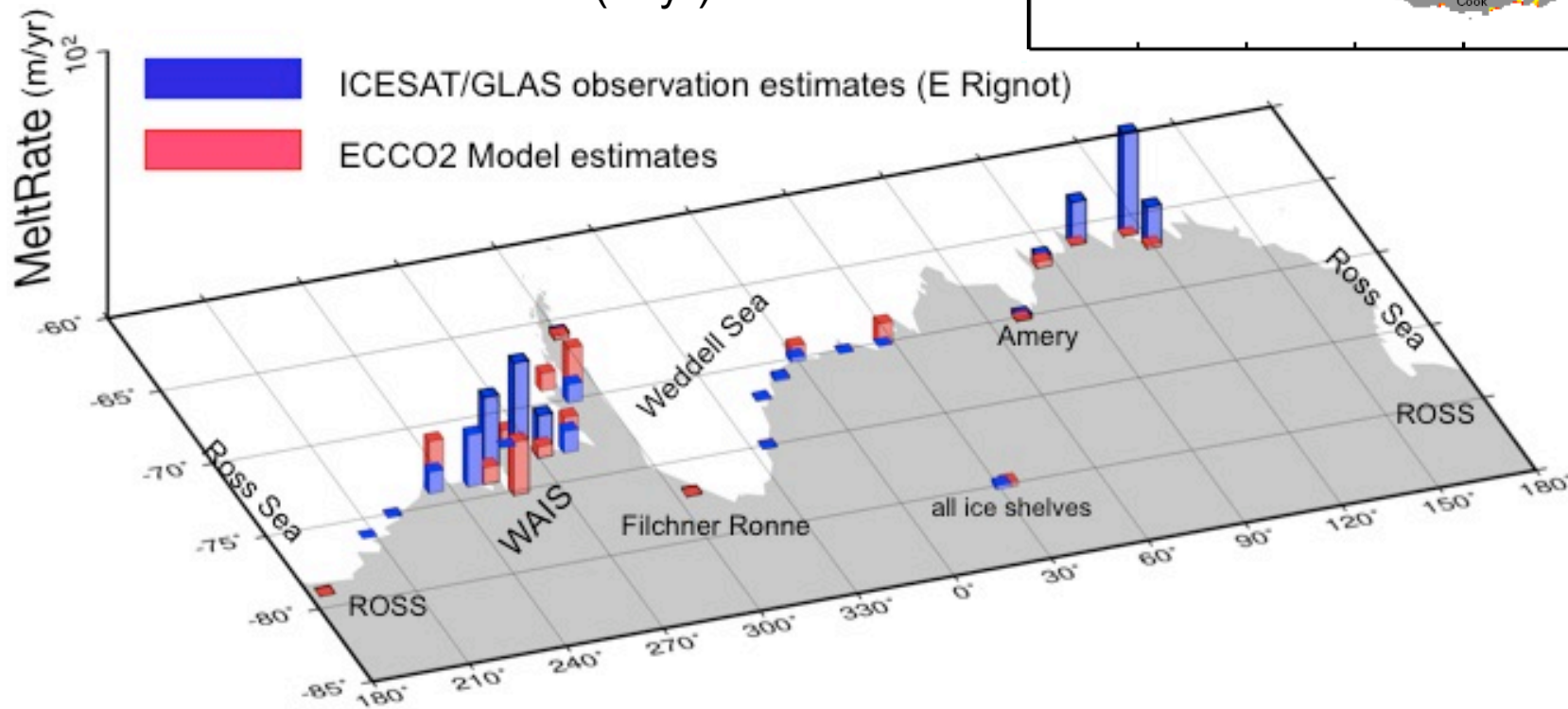**Optimized**

Sloyan & Rintoul, 2001

GRACE
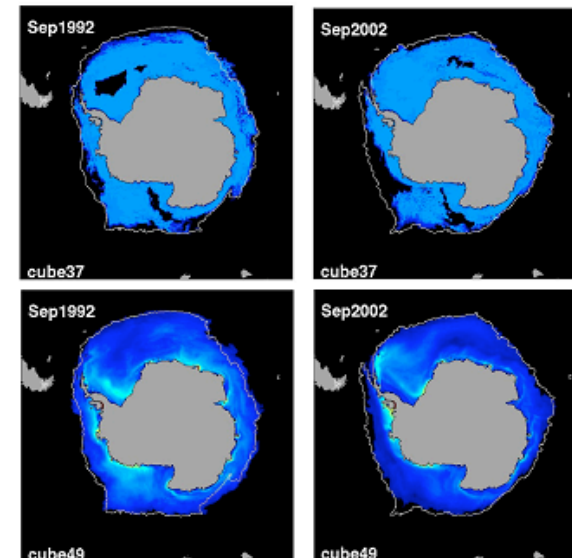
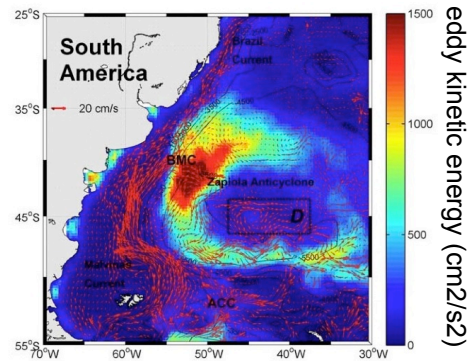# Modeling of ice shelf cavities (M. Schodlok)
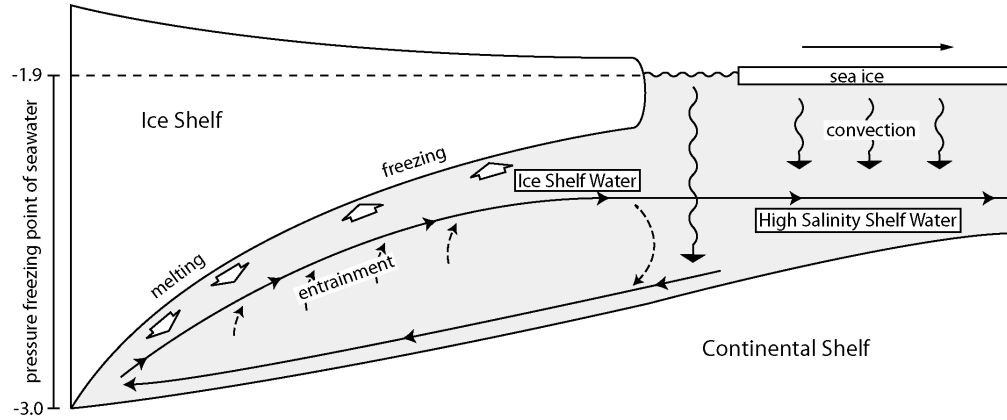
Antarctic ice shelf thickness (m)
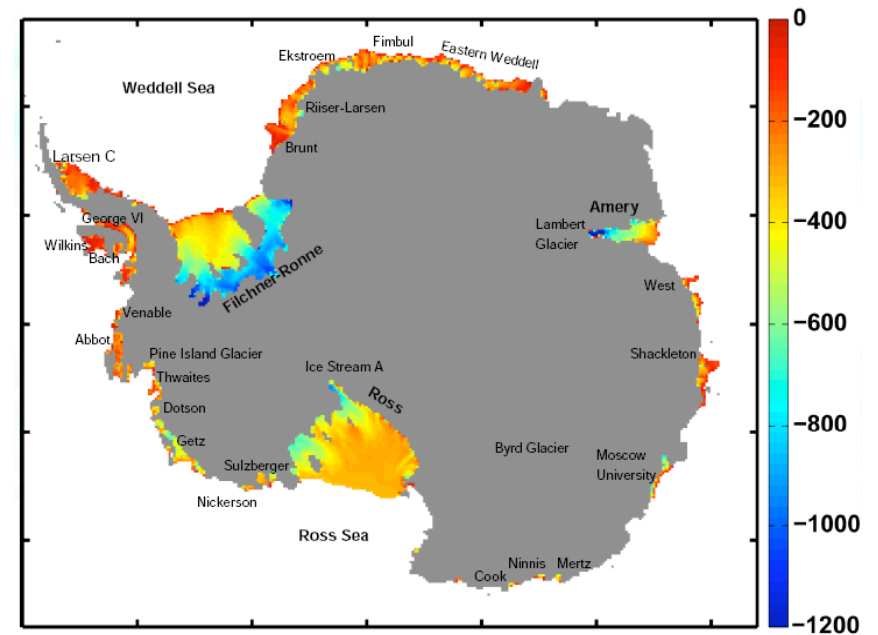
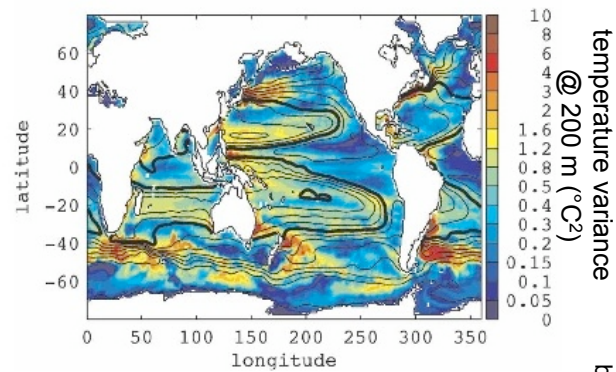## Melt rate dh/dt 2004 (m/yr)

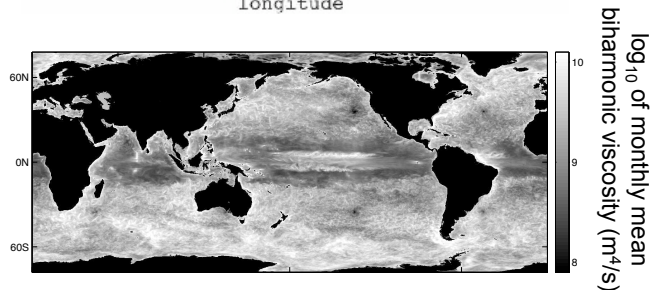# Example eddying ocean circulation studies

eddy kinetic energy (cm2/s2)

The role of vorticity fluxes in the dynamics of the Zapiola Anticyclone (Volkov & Fu, 2008)

zonal propagation (km/day)
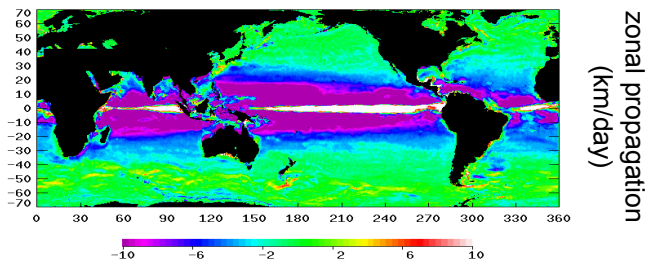
Eddy propagation velocities (Fu, 2006)

temperature variance @ 200 m (°C²)

Estimated global hydrographic variability (Forget & Wunsch, 2007)

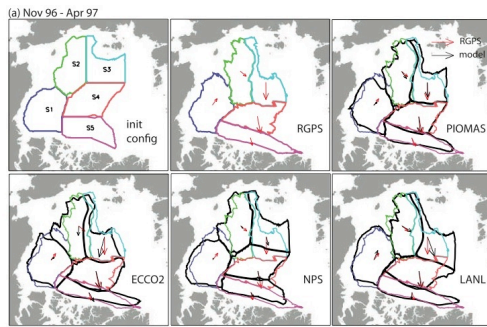log_{10} of monthly mean biharmonic viscosity (m⁴/s)

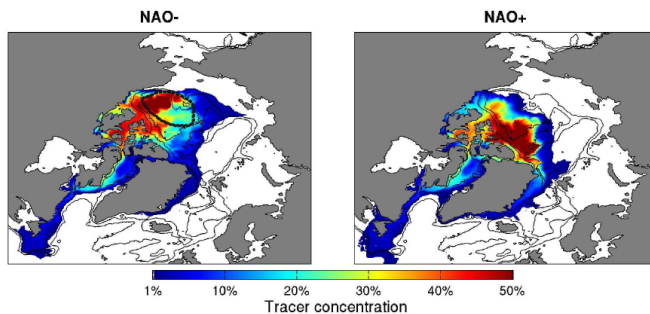Eddy parameterizations (Fox-Kemper & Menemenlis, 2008)
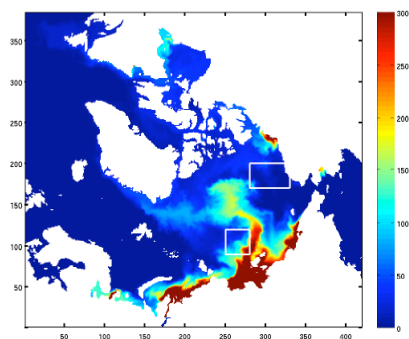
Example Arctic Ocean studies
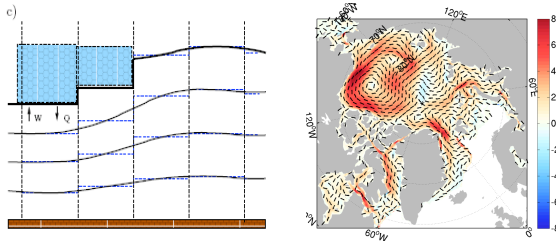
Sea ice model and adjoint development
(Campin et al., 2008; Nguyen et al., in press;
Losch et al., submitted; Heimbach et al., submitted).

Variability of sea ice simulations assessed with RGPS
kinematics (Kwok et al., 2008).

Response of the Arctic freshwater budget to
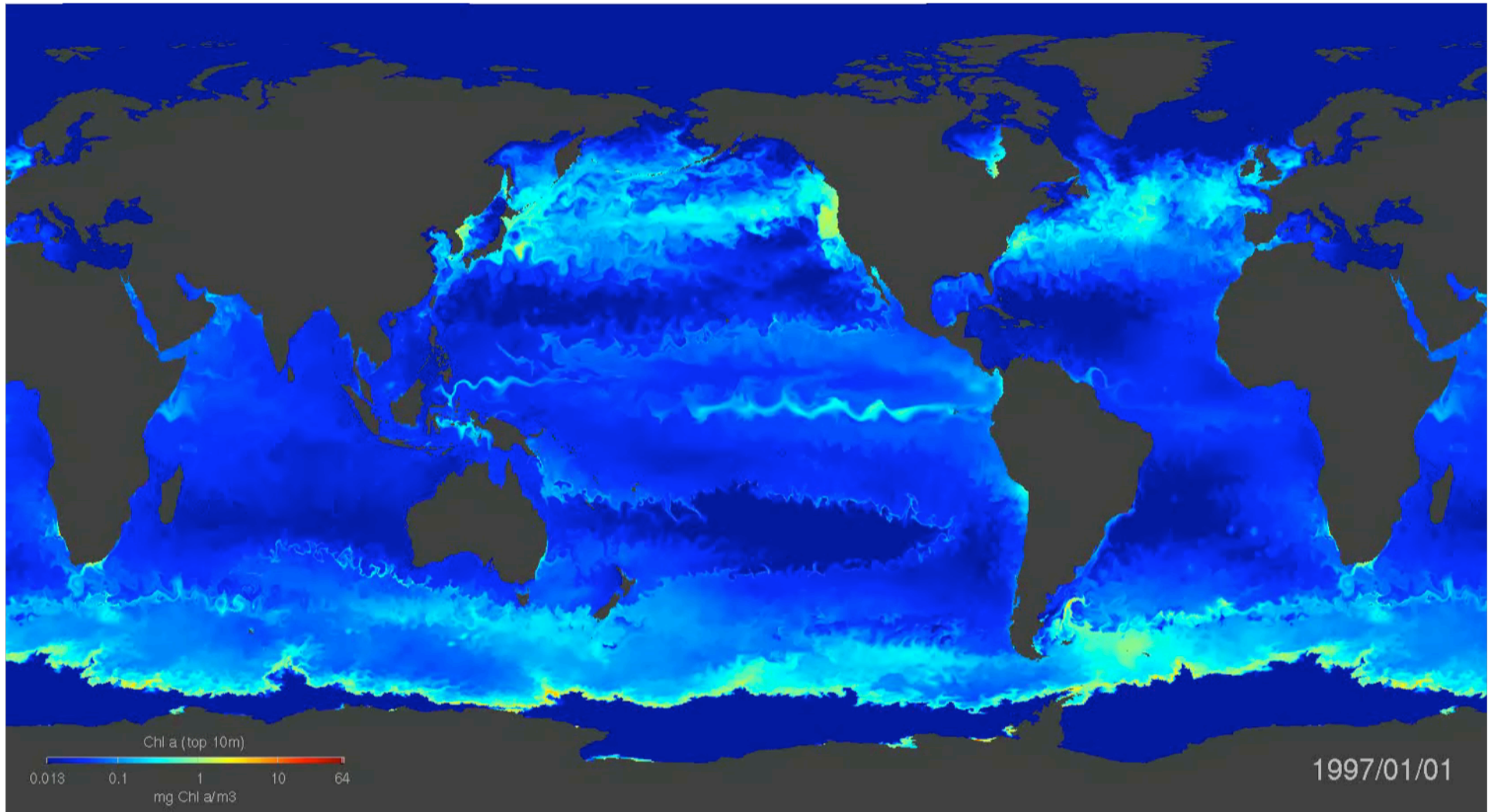extreme NAO forcing (Condron et al., 2009).

Modeling transport, fate and lifetime of riverine DOC in the
Arctic Ocean (Manizza et al., in press).

Example ocean biogeochemistry study

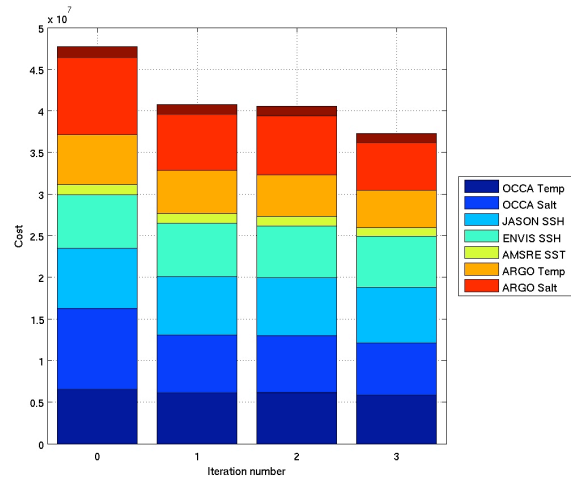## Regulation of phytoplankton diversity by ocean physics
(M. Follows, A. Barton, S. Dutkiewicz, J. Bragg, S. Chisholm, C. Hill, & O. Jahn)
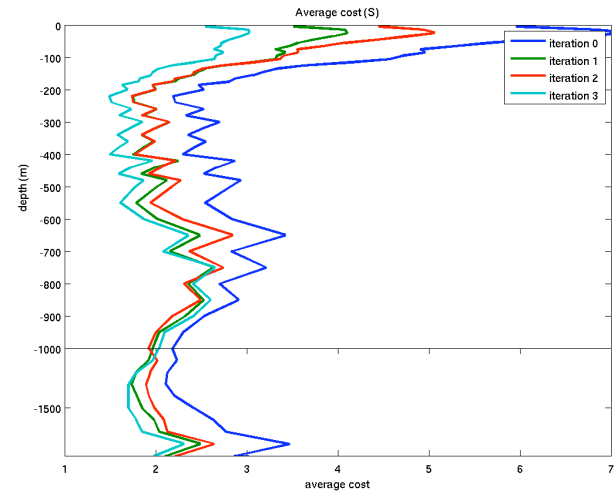

Chlorophyll-a estimated using a self-assembling ecosystem model

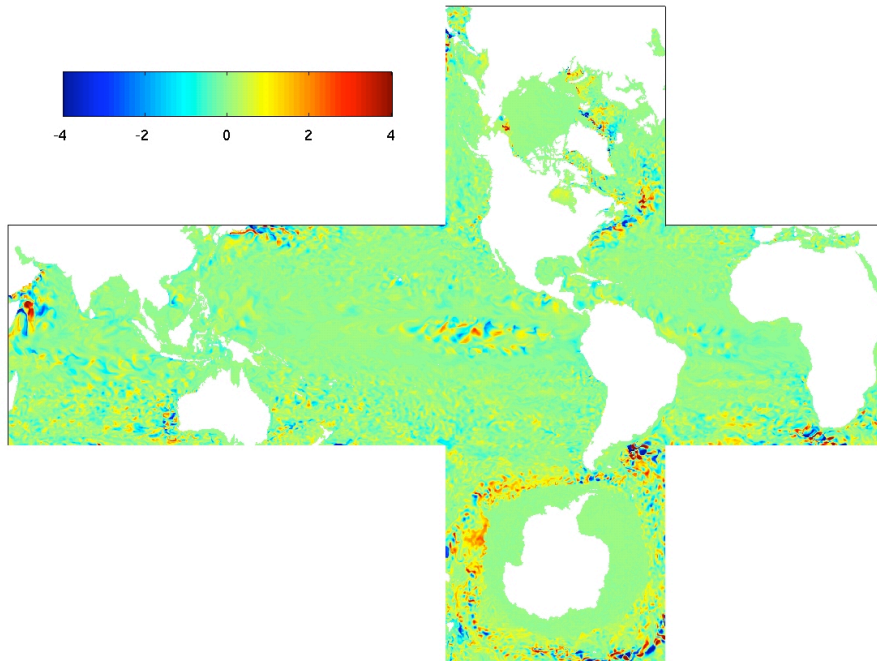# CS510 adjoint optimization during ARGO period (H. Zhang)
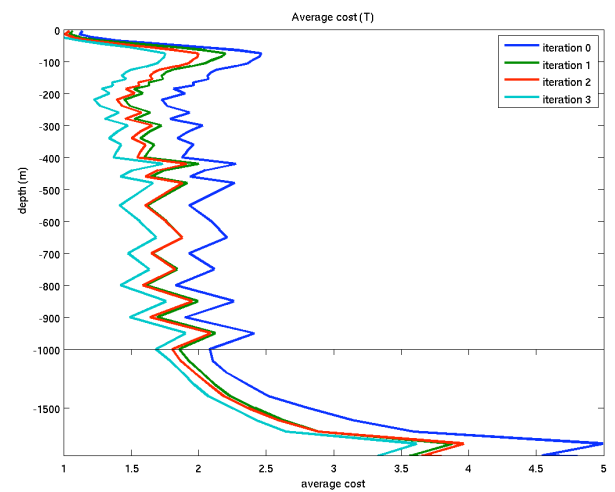
Cost function reduction

Cost function reduction
vs ARGO salinity

Iteration 3 vs baseline SST change on Aug 27, 2004

Cost function reduction
vs ARGO temperature

Summary

ECCO2 is demonstrating feasibility and utility of physically consistent ocean data assimilation in the presence of eddies and ice.

A first solution was obtained using a Green's function approach to adjust a small number (~80) of model parameters.

Ocean model includes explicit representation of Antarctic ice shelf cavities.

Early science applications include impact of mesoscale eddies on large-scale ocean circulation, studies of polar oceans, and ocean biogeochemistry,

A follow-on solution is being obtained during the ARGO period using the adjoint method to adjust ~10^9 model parameters.

ECCO2 solutions and estimation tools are available at **http://ecco2.org/**